ONR Graduate Traineeship Award in Ocean Acoustics for Sunwoong Lee

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LONG-TERM GOALS

The long-term goal of this research is to develop optimal array signal processing techniques for passive source localization in littoral shallow-water environments. It has long been known that multi-modal dispersion in a shallow water waveguide degrades the performance of bearing estimates by conventional plane-wave beamforming. This is due to spurious effects unique to the waveguide environment such as multiple peaks and beam spreading in the beamformer output [1, 2]. We have developed array signal processing techniques that account for and exploit multi-modal wave propagation and dispersion.

OBJECTIVES

The primary objectives of the research are to:

- Develop the *array invariant* passive localization techniques that require little *a priori* knowledge of the wave propagation environment.

- Instantaneously and simultaneously localize multiple sources in a shallow-water waveguide without extensive computations and without ambiguity.

APPROACH

The array invariant method for passive localization of impulsive sources has been theoretically derived and experimentally demonstrated in FY05 effort using the data acquired form the Acoustic Clutter Experiment in 2001 and 2003. It has been shown that simple and robust passive source localization is possible using the array invariant method without *a priori* knowledge of environmental parameters. We have extended the array invariant method for range and bearing estimation of a broadband random noise source that is not necessarily impulsive in the time domain, while maintaining the advantages of the array invariant method for impulsive source localization. We have theoretically and numerically

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1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **ONR Graduate Traineeship Award in Ocean Acoustics for Sunwoong Lee**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,77 Massachusetts Avenue,Cambridge,MA,02139**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

shown that the array invariant method can be used not only for localization of a single source, but for simultaneous localization of multiple noise sources in an ocean waveguide without ambiguity.

WORK COMPLETED

The research work in Fiscal Year 2006 was a great success in extending the *array invariant* source localization techniques in a dispersive waveguide that require little *a priori* knowledge of the environment. The extended array invariant techniques enable instantaneous and simultaneous localization of multiple random noise sources in a horizontally-stratified ocean waveguide from passive beam-time intensity data obtained after conventional plane-wave beamforming of acoustic array measurements.

Localization of multiple sources using the array invariant method has advantages over the conventional triangulation method using two arrays. First, the array invariant method does not require two arrays with sufficient spatial separation, which is a significant advantage when the localization is made from a mobile platform. Second, the array invariant method does not suffer from the ghost source problem typical in the triangulation method when there are multiple sources present [3]. The array invariant method is significantly advantageous over MFP, where unambiguous source range estimation is nearly impossible even with accurate environmental knowledge, when there are unknown number of multiple, spatially stationary sources in an ocean waveguide [4, 5].

RESULTS

We have previously shown that the localization of an impulsive source can be achieved using the array invariant method without requiring the a priori knowledge of environmental parameters and without extensive computations [6]. We have further extended the method to show that the array invariant method can be applied for localization of a broadband random noise sources. This is achieved by cross-correlating the beam-time series with the time series measured by the acoustic sensor at the center of the array [7].

We first show that the range and bearing of a broadband random noise source can be determined using the extended array invariant method. The source is located at $r_o = 5$ km and $\theta_o = 60°$ as shown in Fig. 1. The environment is 100-m deep Pekeris waveguide with sand bottom. The source and the receiving array depths are 50 m and 30 m, respectively. The aperture of the receiving array is 150 m. The source power spectral density is assumed to be 0 dB re 1 μPa^2 / Hz within the 390 to 440-Hz frequency band.
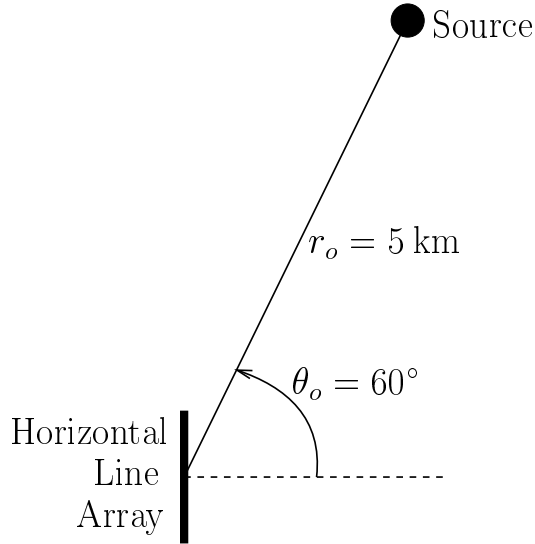
Figure 1: Top view of the geometry for the single source localization example. The source is at 60° from the broadside of the horizontal receiving array, and at 5-km range.
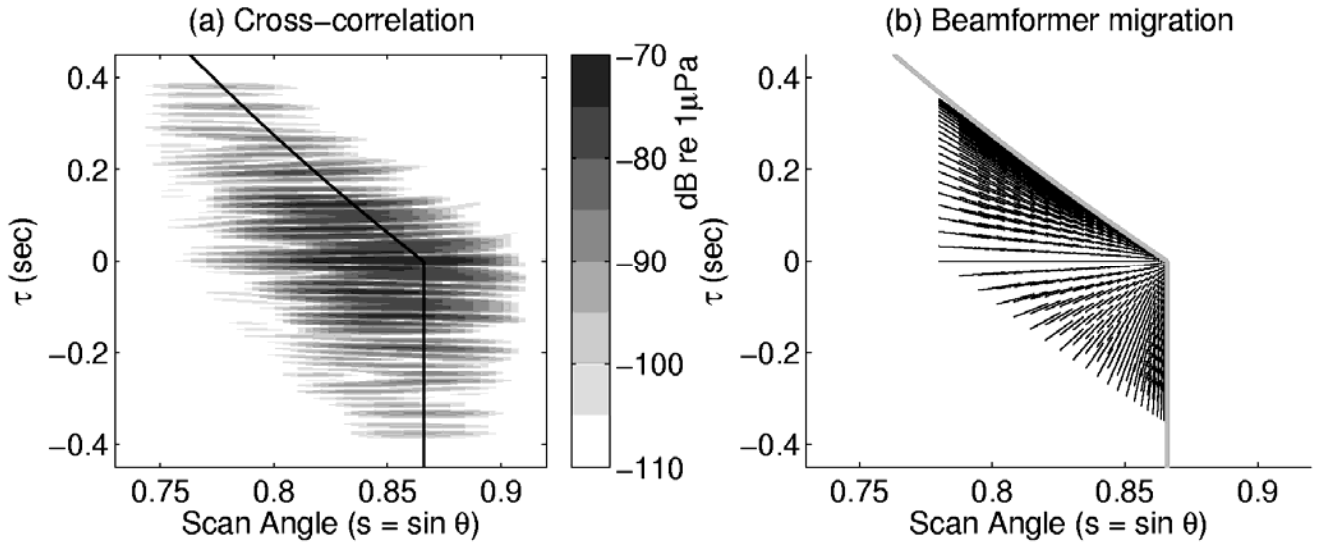

Figure 2: The cross-correlated intensity field for the source-receiver geometry shown in Fig. 1 in the sand-bottom Pekeris waveguide environment. The black solid line overlain in the $\tau > 0$ domain is the beamformer migration line in terms of the reduced travel time. The black solid line in the $\tau < 0$ domain is at $\sin\theta_o$.

The cross-correlated intensity field $I_{Bo}(s, \tau)$ is shown in Fig. 2, where $s = \sin\theta$ is the array scan angle, and τ is the delay time. Two black solid lines are overlain on Fig. 2. One line in the $\tau > 0$ domain is the beamformer migration line $\tilde{s}(\tau)$ for an impulsive source in an ideal waveguide as defined in Eq. (8) of

Ref. [6], and the other line in the $\tau < 0$ domain marks the source bearing $\sin\theta_o$. These two lines show that the cross correlated intensity field is bounded by these lines except that the field is smeared by the beampattern of the horizontal receiving line array. Given these two bounding lines in the cross-correlated intensity field, we can estimate both source range and bearing without ambiguity.

In order to identify these two bounding lines from Fig. 2, we apply an image transform technique similar to the Radon transform [8] to the cross-correlated beam-time image. In this transform, a given image is integrated along a semi-infinite line starting from $(s, 0)$ and having an angle ϕ_r from the positive τ-axis in the clockwise direction. Now we show that both the range and bearing of the source can be extracted from the transformed intensity field in Fig. 3.
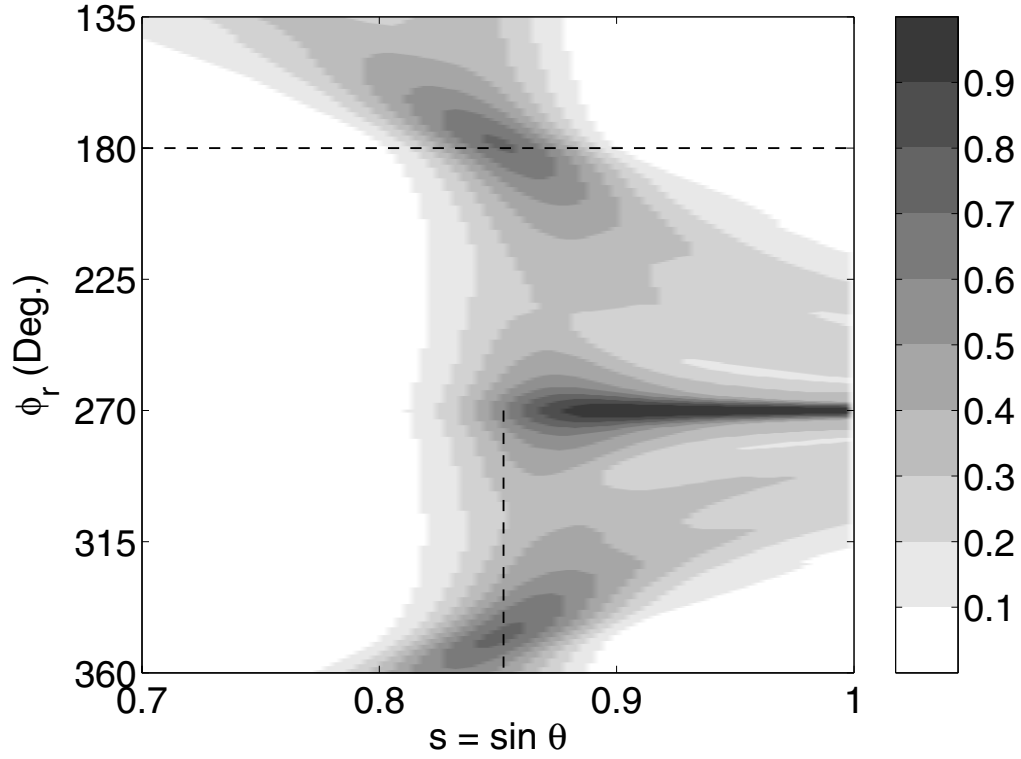

Figure 3: The transformed intensity image $I_n(s, \phi_r)$ of the cross-correlated intensity image in Fig. 2.

First, the bearing of the source can be estimated from the value of s where the maximum of $I_n(s, \phi_r = 180°)$ occurs. In Fig. 3, this peak is seen to occur at $\hat{s}_o = 0.853$ or $\hat{\theta}_o = 58.5°$. This is within 3\% of the true source bearing $\theta_o = 60°$. Second, once the bearing of the source has been estimated, the range of the source can be estimated using

$$\hat{r}_o = -\frac{c(z)\sin\hat{\theta}_o}{\tan\hat{\phi}_r},$$

where $\hat{\phi}_r = \arg\max_{\phi_r} I_n(s = \hat{s}, \phi_r)$. In Fig. 3, this peak occurs at $\hat{\phi}_r = 346.7°$. The range of the source is then estimated to be $\hat{r}_o = 5.4\,\text{km}$, which is within 10% of the true source range.

The approach used for localization of a single source can also be used for localization of multiple uncorrelated random noise sources in an ocean waveguide in both range and bearing. Here we consider the case where there are 3 uncorrelated noise sources S_1, S_2, S_3, as shown in Fig. 4. The source S_1 is at range $r_1 = 8.2$ km and bearing $\theta_1 = 45^\circ$. The other two sources S_2 and S_3 are at the same bearing $\theta_2 = \theta_3 = 60^\circ$, and their ranges are $r_2 = 3$ km and $r_3 = 10$ km, respectively. We assume that these three sources have the same source power spectrum of 0 dB re 1 μPa^2 / Hz in the 390 to 440 Hz frequency band, but they are uncorrelated with each other.
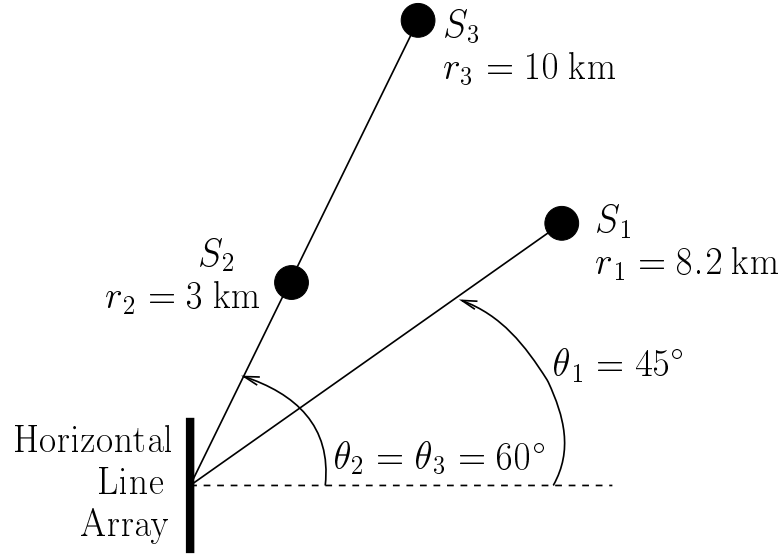

Figure 4: Top view of the geometry for the multiple source localization example. All 3 sources are at 30-m depth, and the receiver array depth is 50 m. The receiver array aperture is 150 m.

The cross-correlated intensity field $I_{Bo}(s,\tau)$ for this multiple source scenario is shown in Fig. 5. The cross-correlated intensity in Fig. 5 exhibits two distinct intensity fields when $\tau < 0$, one at the bearing of S_1, and the other at the bearing of S_2 and S_3. When $\tau > 0$, the field for S_2 and S_3 splits into two distinct fields, since their ranges from the receiver array are different. The cross-correlated intensity field for S_1 when $\tau > 0$ shows the same pattern as that of the single source scenario.
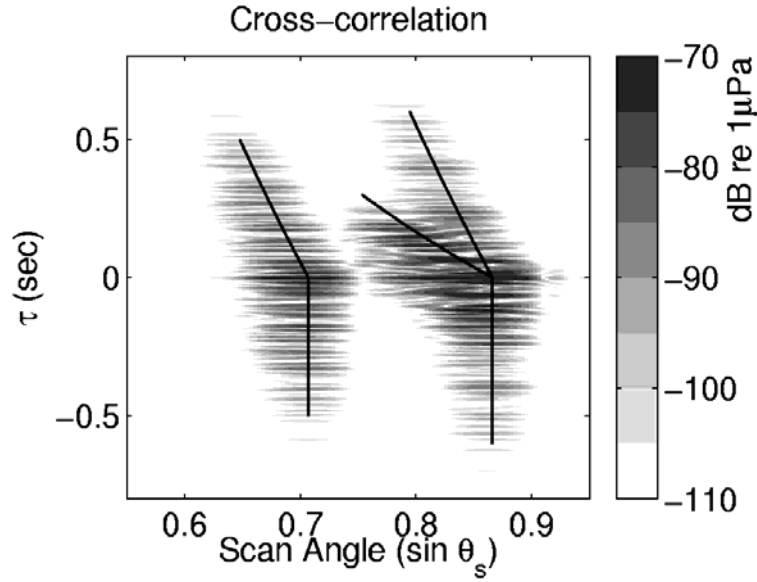
Figure 5: The cross-correlated intensity field $I_{Bo}(s,\tau)$ ***for the source-receiver geometry shown in Fig. 4. The two black solid lines overlain in the τ < 0 domain marks*** $\sin\theta_1$ ***and*** $\sin\theta_2$ ***, respectively. The three black solid lines in the τ > 0 domain are the beamformer migration lines for sources S₁, S₂, and S₃ in terms of the reduced travel time.***

We now can apply the image transform method previously introduced for localization of single source, and localize all three sources in range and bearing without ambiguity. The detailed procedures and estimation results are provided in Ref. [7].

IMPACT/APPLICATIONS

The array invariant method developed from Fiscal Year 2006 effort has significant advantages over existing source localization methods for practical source localization scenarios. This is because the array invariant method does not require *a priori* knowledge of the environmental parameters, nor does it require extensive computations.

The array invariant method has tremendous potential application in shallow-water surveillance missions and anti-submarine warfare. The method enables instantaneous and simultaneous localization of multiple broadband noise sources in a littoral environment using towed arrays from surface ships or submarines.

REFERENCES

[1] C. S. Clay. Array steering in a layered waveguide. *J. Acoust. Soc. Am.*, 33(7):865-870, 1961.

[2] N. C. Makris and P. Ratilal. A unified model for reverberation and submerged object scattering in a stratified ocean waveguide. *J. Acoust. Soc. Am.*, 109(3):909-941, 2001.

[3] D. H. Johnson and D. E. Dudgeon, *Array Signal Processing*, Prentice Hall, Upper Saddle River, 1993.

[4] M. D. Collins, L. T. Fialkowski, W. A. Kuperman, and J. S. Perkins. The multi-valued Bartlett processor and source tracking. *J. Acoust. Soc. Am.*, 97:235-241, 1995.

[5] M. V. Greening, P. Zakarauskas, and S. Dosso. Matched-Field localization for multiple sources in an uncertain environment, with application to Arctic ambient noise. *J. Acoust. Soc. Am.*, 101:3525-3538, 1997.

[6] S. Lee, N. C. Makris, The array invariant, *J. Acoust. Soc. Am.* **119**(1), 336-351, 2006.

[7] S. Lee, *Effcient Localization in a Dispersive Waveguide: Applications in Terrestrial Continental Shelves and on Europa*, PhD thesis, Massachusetts Institute of Technology, Cambridge, 2006.

[8] S. R. Deans. Radon and Abel transform. In A. D. Poularikas, editor, *The Transforms and Applications Handbook*, chapter 8. CRC Press, Boca Raton, 2nd edition, 2000.

PUBLICATIONS

- S. Lee, N. C. Makris, "The array invariant," *J. Acoust. Soc. Am.* **119**(1), 336-351, 2006.

- S. Lee, N. C. Makris, "Range estimation of broadband noise sources in an ocean waveguide using the array invariant," *J. Acoust. Soc. Am.*, **117**(4), 2577, 2005.

- N. C. Makris, S. Lee, A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data, *Proceedings of 1st International Conference on Underwater Acoustic Measurements: Technologies and Results*, 1233-1236, 2005.

- S. Lee, N. C. Makris, Range estimation of broadband noise sources in an ocean waveguide using the array invariant, *J. Acoust. Soc. Am.* 117, 2577, 2005.

- P. Ratilal, S. Lee, Y. Lai, T. Chen, D. Symonds, N. Donabed, N. C. Makris, Range-dependent 3D scattering and reverberation in the continental shelf environment from biology, geology and oceanography, *J. Acoust. Soc. Am.* 117, 2611, 2005.

- S. Lee, N. C. Makris, A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data, *J. Acoust. Soc. Am.* 116, 2646, 2004.

- S. Lee, P. Ratilal, N. C. Makris, Explaining extended linear features observed in remote sonar images of the New Jersey continental shelf break during Acoustic Clutter Experiments in 2001 and 2003, *J. Acoustic. Soc. Am.* 115, 2618, 2004.